

## Analysis of the influence of the water balance process on the change of landscape patterns in the upper reaches of the Yangtze River

Yuting Liu\*, Jijun Xu, Zhe Yuan and Zhigui Sha

Department for the Integrated Use of Water Resources, Yangtze River Scientific Research Institute, Yangtze Water Resources Committee, Wuhan, 430010 China

\*Corresponding author. E-mail: 1990688789@qq.com

### ABSTRACT

Based on hydrometeorological data and land-use data (from 1980 to 2015), the effects of water balance on landscape patterns in the upper reaches of the Yangtze River were studied using water balance analysis, the landscape index method, and other methods. Eight appropriate landscape indices (NP, COHESION, LPI, AI, SHDI, CONTAG, SPLIT, and LS) were selected to explore the spatial and temporal characteristics of landscape patterns. From 1980 to 2015, the precipitation in the study area decreased by 6.97%, and the annual precipitation of farmland was maintained at about 1,050 mm. The evapotranspiration (ET) had little change in general, but it varies greatly under different land-use types. Soil water storage variables showed a downward trend, and soil water storage variables of various land-use types changed dramatically during the study period. The total number of patches increased and the patch shape became more complex. At the level of landscape structure, SHDI and SPLIT increased, while CONTAG and COHESION decreased, and the degree of patch fragmentation and landscape heterogeneity improved. Correlation analysis showed that from a time perspective, LSI, SPLIT, and SHDI were significantly negatively correlated with ET, and CONTAG was significantly positively correlated with ET. There was a significant negative correlation between SPLIT and soil water (SW), and a significant positive correlation between COHESION and SW. These results indicated that with the decrease of ET and soil water storage variables, patches became more dispersed and landscape patterns became more fragmented. From the perspective of spatial distribution, the increase of SW increased landscape diversity and decreased landscape connectivity and contagion. The correlation coefficients between SW and the three groups of landscape pattern indexes (SHDI, CONTAG, and COHESION) were higher than those between ET and the three groups of landscape pattern indexes, which meant that soil water is more correlated with landscape pattern characteristics, and the effect of soil water change on landscape heterogeneity is more obvious. The study of the relationship between hydrological processes and landscape pattern characteristics in this paper enriches and expands the theoretical method system of ecological hydrology and ecological environmental protection in arid/semi-arid regions in our country.

**Key words:** Landscape indices, Landscape pattern, Land use/cover, Upper Yangtze River Basin, Water balance

### HIGHLIGHTS

- We evaluated the changes in hydrological regimes and the temporal and spatial characteristics of landscape patterns in the upper reaches of the Yangtze River.
- This study has revealed, for the first time, the influence mechanism of evapotranspiration and soil water storage variables on landscape patterns in the upper reaches of the Yangtze River.

## 1. INTRODUCTION

An ecosystem is a foundation for the existence and development of human society, and the continued stability of its structure and function has become a prerequisite for the development of human society. Deeper research has been conducted from the natural forest ecosystems in different natural zones to the hydrological effects of soil and water conservation ecological construction in the semi-arid loess plateau. At the same time, the study of the impact of changes in hydrological processes on oasis vegetation has also made great progress in recent decades (Zhou *et al.*, 2011; Chen & Li, 2019; Feng *et al.*, 2020). An ecosystem is very sensitive to the water balance process. After decades of exploration, scholars all over the world have recognized that the hydrological processes are the basic driving mechanisms for the formation, development, and evolution of ecosystems (Li *et al.*, 2011; Ma *et al.*, 2020). Water cycle and water balance are some of the most important functions and characteristics of ecosystems (Yang *et al.*, 2006). Hydrological processes can alter the biochemical cycle of an ecosystem and affect the transport of nutrients between soil and vegetation, thereby altering the productivity and affecting the structure and function of an ecosystem (Xiao *et al.*, 2003; Liu *et al.*, 2014; Gao, 2020). With the rapid development of society and economy in China, the intensity of exploitation and utilization of water and soil resources is increasing, and the degradation and atrophy of the ecosystem are extremely serious (Zhang, 2018). As a consequence, identifying the degree of influence of hydrological elements on changes in the structure and function of the ecosystem has important guiding significance for the restoration and protection of the ecosystem, and it is also the basis for ensuring ecological health and sustainable development of the river basins.

Studying the dynamic changes in landscape patterns and their response to hydrological processes is a research hotspot in the field of water resources management and terrestrial ecological environment in river basins (Lou, 2015; Pan *et al.*, 2019; Wu *et al.*, 2020). To understand the landscape pattern itself and its interaction with ecological processes, it is crucial to understand how spatial heterogeneity changes continuously in the landscape. Among the influencing factors of landscape patterns, the shorter time scale, such as the ecological environment change within the 100-year scale, and the climatic conditions and their changes are the decisive factors. Global precipitation evapotranspiration (ET) and soil water storage variables are important climatic factors affecting vegetation dynamics (Li *et al.*, 2019). Changes in regional hydrological factors such as precipitation, ET, and soil water storage variables will directly or indirectly lead to changes in land use and vegetation coverage, which will lead to changes in landscape patterns at different scales (Wang *et al.*, 2005; Liu *et al.*, 2018). Previous studies have shown that precipitation determines vegetation coverage and biomass. At the landscape pattern scale, the redistribution of precipitation between different landscapes or the spatiotemporal distribution patterns of water is the main factor affecting vegetation patterns and community structure (Wang, 2017). Soil moisture is a key factor that links the influence of the atmosphere, soil, and vegetation on the water cycle process with the influence of the water cycle on the vegetation pattern. It controls the spatiotemporal distribution patterns of vegetation by adjusting the interaction of the atmosphere–soil–vegetation system (Lou, 2015). Landscape pattern characteristics and changes have important effects on ecosystem functions and processes, which are the most interesting questions for ecologists to study ecosystem functions and processes at different scales (Cook, 2002; Chen *et al.*, 2013a, 2013b; Ramalho *et al.*, 2014). At present, the research methods of landscape patterns mainly include the landscape index method, landscape ecology model, and spatial statistics method (Yu *et al.*, 2011). The landscape index method can be used to quantitatively analyze the regional landscape pattern change on a larger scale, reflect the response of landscape patterns to the change of hydrological factors to a certain extent, explore the ways to improve landscape patterns, and promote sustainable development of ecosystems (Yan *et al.*, 2005; Xu *et al.*, 2020).

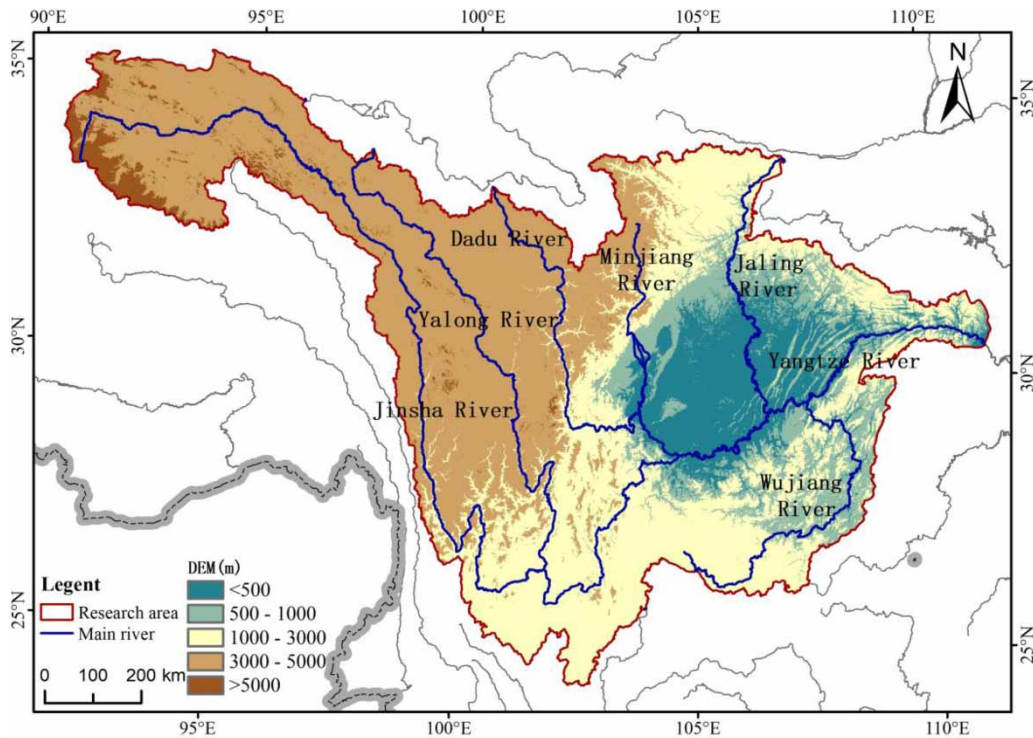
As a major ecological barrier in China, the UYRB has an important ecological strategic position in the Yangtze River Basin and the whole country because of its complex and diverse ecological system, rich biodiversity, and special natural environment (Wu *et al.*, 2010). In recent decades, the development of the regional economy and the formulation of macroeconomic policies have driven changes in the land-use structure in the UYRB (Wu *et al.*, 2008). Meanwhile, it has also caused a series of ecological and environmental problems, such as serious soil erosion, frequent natural disasters, reduced biodiversity, and decreased land quality (Pan *et al.*, 2004). Ren *et al.* (2013) found that the ecosystem degradation in the UYRB was in a serious state, on the whole, especially the threat of ecological degradation of forest, grassland, and farmland systems. At the same time, the environmental protection measures in the UYRB have made some progress. The implementation of many ecological projects, such as the Natural Forest Resources Protection Project, the Yangtze River Protective Forest Project, and the Project of Returning Farmland to Forests, had effectively improved the ecological environment (Ma *et al.*, 2012). The research on the water balance process and the spatial distribution of landscape patterns in this region are conducive to the rational development and utilization of water and soil resources, and the simultaneous economic development and ecological protection under the premise of environmental protection. However, as an important indicator reflecting landscape patterns, there are few studies on the relationship between the landscape index and the hydrological process, and current studies focus more on the impact of different land-cover types on water balance, while there are few studies on the impact of water balance on landscape patterns. Therefore, this paper takes the UYRB as the research area to explore the impact of water balance on landscape patterns, in order to analyze and understand the characteristics of landscape pattern changes from a new perspective, and to provide a scientific basis for local water resources management and land-use planning. The objectives of this research are: (1) to extract the landscape spatial pattern indices based on the land-use data; (2) to obtain the hydrological elements of different land-use types during 1980–2015; and (3) to analyze the influence of the water balance process on the spatiotemporal distribution of landscape patterns.

## 2. MATERIALS AND METHODS

### 2.1. Study area and data sources

#### 2.1.1. Study area

The UYRB is the section from Geradandong, Qinghai-Tibet Plateau to Yichang, Hubei Province (90–105°E, 25–36°N), with a total length of 4,500 km and a total area of about 1 million km<sup>2</sup> (Figure 1). The topography and altitude of the study area vary greatly. The altitude rises from 265 to 6,492 m from east to west, among which the areas above 4,000, 3,000–4,000, and below 1,000 m account for 31, 12, and 25%, respectively. The study area spans three climate zones, namely the plateau climate zone, the northern subtropical zone, and the mid-subtropical zone (Chen *et al.*, 2013a, 2013b). Among them, the Qinghai-Tibet Plateau has an average altitude of 4,000 m and a dry and thin atmosphere, with an average annual temperature of 8–10 °C. The average annual temperature of most areas in the lower reaches of the plateau is 16–18 °C (Wang *et al.*, 2016). Affected by the warm and humid ocean current and the subtropical high pressure in the western Pacific, the distribution of precipitation decreases from east to west and from south to north. The annual precipitation in the region is 800–1,200 mm, which is characterized by uneven spatiotemporal distribution (Ye *et al.*, 2014). The UYRB has rich water resources, and the river runoff accounts for 40% of the whole Yangtze River and 15% of the whole country. Due to the variety of terrain and landform and the climate changes, the vegetation types are also quite different (Chen *et al.*, 2017).



**Fig. 1** | Location of the study area.

### 2.1.2. Data sources

**DEM Data.** The DEM (Digital Elevation Model) data were downloaded from the Resource and Environmental Data Cloud Platform (RESDC) (<http://www.resdc.cn/>) with a spatial resolution of 1 km.

**Land-use/-cover data.** Seven periods of national land-use data in 1980, 1990, 1995, 2000, 2005, 2010, and 2015 were chosen from the Data Center for Resources and Environmental Sciences of the Chinese Academy of Sciences (<http://www.resdc.cn/>). These data took Landsat TM/ETM remote sensing images as the main data source with a spatial resolution of 1 km. Combined with the classification of China's terrestrial ecosystem by Xie *et al.* (2008) in 2015 and the actual situation in the UYRB, seven land-use types, namely farmland, forest, grassland, lake/river, construction land, wetland, and desert were mainly counted, and the swamp was included in the scope of wetland.

**Meteorological data.** The precipitation data and the temperature data during 1980–2015 were obtained from the  $0.5^\circ \times 0.5^\circ$  raster meteorological data set provided by the China Meteorological Data Network (<http://data.cma.cn/>), which were resampled to a spatial resolution of 1 km to match with land-use data by ArcGIS.

## 2.2. Methods

### 2.2.1. Water balance analysis

During the hydrological cycle of a particular region, the water budget is determined by a balance between incoming and outgoing water, and the water storage capacity is determined by the surface profile and underlying surface conditions of the landscape (Li *et al.*, 2008). Precipitation and ET are the most important factors affecting water balance, so they must be seriously considered in the study of the water balance process.

### (1) Precipitation

The monthly raster data of  $5 \text{ km} \times 5 \text{ km}$  were obtained through projection transformation, clipping, resampling, and summation of daily data.

### (2) Evapotranspiration

There are many methods and empirical models for estimating evaporation, but the monthly land-surface evaporation empirical model proposed by Koichiro Takahashi is widely used at present, which has been well verified in the calculation of surface evaporation in some areas (Koichiro, 1979). The formula for this model is as follows:

$$PE_m = \frac{3100p}{3100 + 1.8p^2 \exp\left(-\frac{34.4t}{235+t}\right)} \quad (1)$$

where  $p$  refers to the monthly precipitation (mm);  $t$  refers to the monthly mean temperature ( $^{\circ}\text{C}$ );  $PE_m$  refers to the monthly land-surface evaporation (mm). This formula physically considers the most important factors affecting evaporation (temperature and precipitation), and is based on actual observation data, so the calculated results were more consistent with the actual (Jiang *et al.*, 2012; Lei *et al.*, 2012; Li *et al.*, 2021).

### (3) Soil water storage variables

The soil water storage variable of the watershed is the annual precipitation minus the annual surface evaporation, which is represented by soil water deficit. Surface runoff caused by topographical factors is also taken into account. The runoff coefficient is used to calculate the annual effective precipitation, which is replaced by the annual effective precipitation (the difference between annual precipitation and surface runoff) (Zhang, 2019). According to the USDA-SCS method and the empirical value method, the corresponding relationship of the runoff coefficients of different slopes of  $0-5^{\circ}$  is 0;  $5-10^{\circ}$  is 0.04;  $10-15^{\circ}$  is 0.12;  $15-20^{\circ}$  is 0.2;  $20-25^{\circ}$  is 0.27; and greater than  $25^{\circ}$  is 0.35 (Zhang *et al.*, 2010). The calculation formula is as follows:

$$SD = P(1 - \alpha) - PE \quad (2)$$

where  $SD$  is the soil water deficit (mm);  $P$  is the annual precipitation (mm), which is accumulated by monthly precipitation;  $PE$  is the annual land-surface evaporation (mm), which is accumulated by monthly land-surface evaporation; and  $\alpha$  is runoff coefficient.

## 2.2.2. Calculation of the landscape pattern index

The landscape index is a simple quantitative index reflecting the spatial configuration characteristics of landscape structure composition, which can meet the requirements of quantifying the causes of landscape spatial heterogeneity and its ecological implications (Yan *et al.*, 2001). The landscape index can also realize the comparison of different landscape patterns in the same period, the comparison of the same landscape patterns in different periods, and the comparison of different landscapes in different periods to study the temporal and spatial characteristics of landscape patterns and eco-hydrology more comprehensively and scientifically (Blackburn *et al.*, 2020). This research studies the changing characteristics of the regional landscape patterns from two levels: The first is the landscape patterns characteristic index reflecting the change characteristics of each landscape type at the level of category index. This kind of index can analyze the change of each landscape type in different ways. The other index is the landscape diversity index reflecting the overall landscape change characteristics at the landscape index level. This kind of index can understand the intensity and direction of human activities in the area (Liu, 2017).

At the level of category indicators, the Number of Patch (NP), the Largest Patch Index (LPI), the Connectivity Index (COHESION), and the Aggregation Index (AI) were selected. At the level of landscape indicators, the LPI, the Landscape Shape Index (LSI), the Separation Index (Split), the Contagion Index (CONTAG), and the Shannon Diversity Index (SHDI) were selected (Zhao *et al.*, 2019a, 2019b; Xiong *et al.*, 2020). In this paper, GIS technology and landscape pattern analysis software Fragstats4.2 were used to calculate each landscape pattern index. The ecological significance of each landscape index is shown in Table 1.

### 2.2.3. Correlation analysis

The correlation coefficient  $R$  is used to calculate the fitting degree of the two variables. The calculation formula is as follows:

$$R = \frac{n \sum_{i=1}^n (X_i \times Y_i) - \sum_{i=1}^n X_i \times \sum_{i=1}^n Y_i}{\sqrt{n \sum_{i=1}^n Y_i^2 - \left(\sum_{i=1}^n Y_i\right)^2} \times \sqrt{n \sum_{i=1}^n X_i^2 - \left(\sum_{i=1}^n X_i\right)^2}} \quad (3)$$

The  $F$ -test method is used to test the significance level of  $\alpha = 0.05$  for the results of the correlation analysis. The formula is as follows:

$$F = (n - 2) \frac{\sum_{i=1}^n (X_i^{\wedge} - \bar{X})^2}{\sum_{i=1}^n (X_i - X_i^{\wedge})^2} \quad (4)$$

where  $R$  is the correlation coefficient with a value range of  $-1 \leq R \leq +1$ ;  $X_i$  and  $Y_i$  represent variables of  $i$  year, respectively;  $n$  is the number of years;  $F$  is the value from the  $F$ -test, and  $P$  is the standard to judge whether the  $F$ -test is significant. When  $R$  is positive, it means that the two variables are positively correlated; otherwise, they are negatively correlated. The larger  $|R|$  is, the closer the correlation between the variables is. According to the relevant literature (Jiang *et al.*, 2017; Li *et al.*, 2018), the statistical value of  $F$  can be divided into extremely significant ( $P < 0.01$ ), significant ( $0.01 < P < 0.05$ ), and insignificant ( $P > 0.05$ ).

**Table 1** | Selected landscape metrics and their explanations.

Metric	Explanation	Formula
NP	The number of plaques of each type	The class metrics level
COHESION	The aggregation degree of various landscape types and their spatial distribution characteristics	The class metrics level
LPI	The proportion of the largest patch area to the total area of the landscape	The class metrics level, the landscape metrics level
AI	The spatial distribution of various landscape types	The class metrics level
SHDI	The degree of land use	The landscape metrics level
CONTAG	The spatial information about the landscape type	The landscape metrics level
SPLIT	The degree of patch separation, a larger value indicates a more diffuse distribution of the type	The landscape metrics level
LSI	The complexity of all patch boundaries	The landscape metrics level



### 3. RESULTS

#### 3.1. Spatial distribution of landscape pattern indices

##### 3.1.1. Status and changes of land use

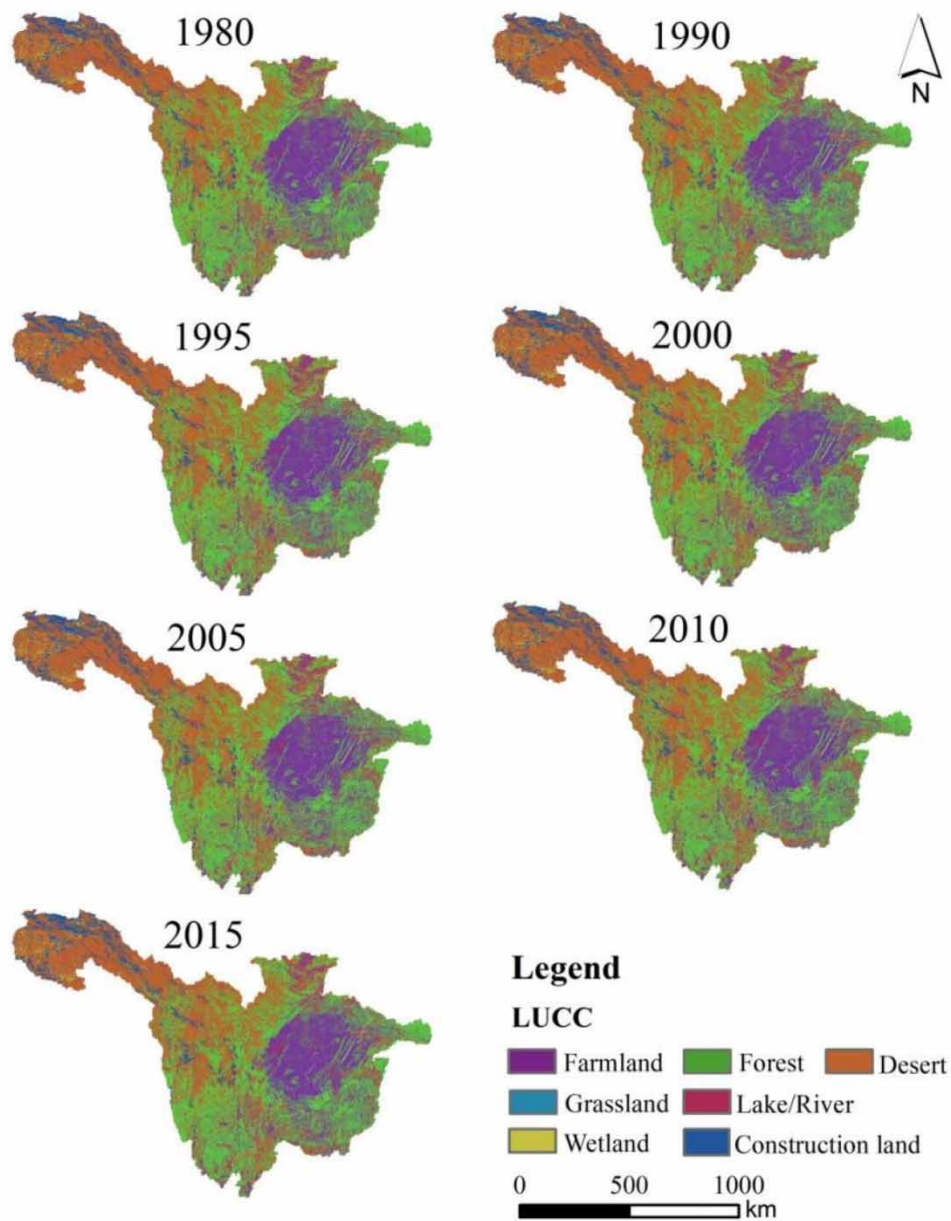
From 1980 to 2015, farmland, forest, and grassland occupied a dominant position in the study area. Due to the development of soil and water conservation and ecological engineering in the Yangtze River, as well as the rapid urban expansion brought about by the economic development of the study area, some farmland and desert had been replaced by construction land, forest, and grassland. The land-use structure had been adjusted to different degrees. Farmland was mainly converted to forest, grassland, and construction land, and desert was mainly converted to grassland. With this trend, the proportion of farmland and desert in the study area decreased by 2.59 and 3.08%, the forest area decreased by 0.13%, and the wetland area decreased by 2.04%. Construction land was the land-use type with the highest increase, with the area increasing from 3,840 km<sup>2</sup> in 1980 to 8,880 km<sup>2</sup> in 2015, with a growth rate of 131%. The area of lakes/ivers increased from 5,956 to 7,070 km<sup>2</sup>, with a growth rate of 18.7% (Figure 2; bold values in Table 2). Since the 1980s, the social and economic level of the UYRB has been significantly improved. Human-intensive development activities have resulted in the reduction and degradation of a large number of high-quality farmland, and the urbanization process has replaced a large amount of farmland and cultivated land with construction land, resulting in a fundamental change in land-use types. In response to the deteriorating ecological environment caused by blind development, the government has implemented a series of ecological projects since the 1980s, such as the Yangtze River shelter-forest system and the 'returning farmland to forest and grassland' on some steep slopes. Due to the construction of water storage facilities and the seasonal changes of glaciers and snow cover, the areas of lake/river area growth were mainly concentrated in the source of the Yangtze River, the Sichuan Basin, and the banks of the Yangtze River mainstream. The large-scale reclamation of arable land and economic construction in the UYRB had an extraordinarily obvious impact on the overall change of landscape patterns.

##### 3.1.2. Characteristics of landscape heterogeneity change

ArcGIS software was used to convert the land-use data into raster data, which was imported into Fragstats4.2 to calculate the landscape indices under different land-use scenarios.

It could be seen from Figure 3 that farmland, forest, and grassland had the largest NPs, accounting for 28.65, 22.27, and 25.29% of the total patch number, respectively, indicating that these landscape types had a dominant position in the entire study area. This is because the economic development of the UYRB is relatively backward, with fewer human activities and high vegetation coverage in most areas. From 1980 to 2015, the NPs in different landscape types changed to different degrees. The NP of farmland changed little from 1980 to 1995 and increased from 2000 to 2015. The NP of grassland gradually decreased from 1990 to 2000, and then changed slowly. The NP of construction land illustrated a gradual upward trend, especially from 3,119 to 4,070 in 2010–2015, with a growth rate of 30.49%. During 2000–2015, the NP of various landscape types increased, indicating that with the continuous and rapid economic development and the influence of population factors, the extent of human development and disturbance to various landscape types in the UYRB had been strengthened, resulting in a gradual increase in landscape fragmentation.

The LPI refers to the percentage of the largest patch area in the landscape area, and it is a measure of the degree of dominance at the patch level (Rong, 2007). Large patches can accommodate more species, which is of great significance in landscape ecology. The LPI of various landscapes is in order of grassland, farmland, forest, desert, lake/river, construction land, and wetland. The UYRB had widespread areas of interlinked grassland and farmland, forming large patches, which were conducive to the storage of materials and energy. The LPI of



**Fig. 2** | Land-use distribution in the UYRB.

lake/river, construction land, and wetland was small, and patches were relatively dispersed, which was conducive to the diffusion and transfer of materials and the flow of energy. According to the LPI (Figure 3), the LPI of farmland decreased gradually, purporting that farmland patches became more fragmented, and the LPI of construction land increased from 0.01 in 1980 to 0.05 in 2015, with an obvious increasing trend.

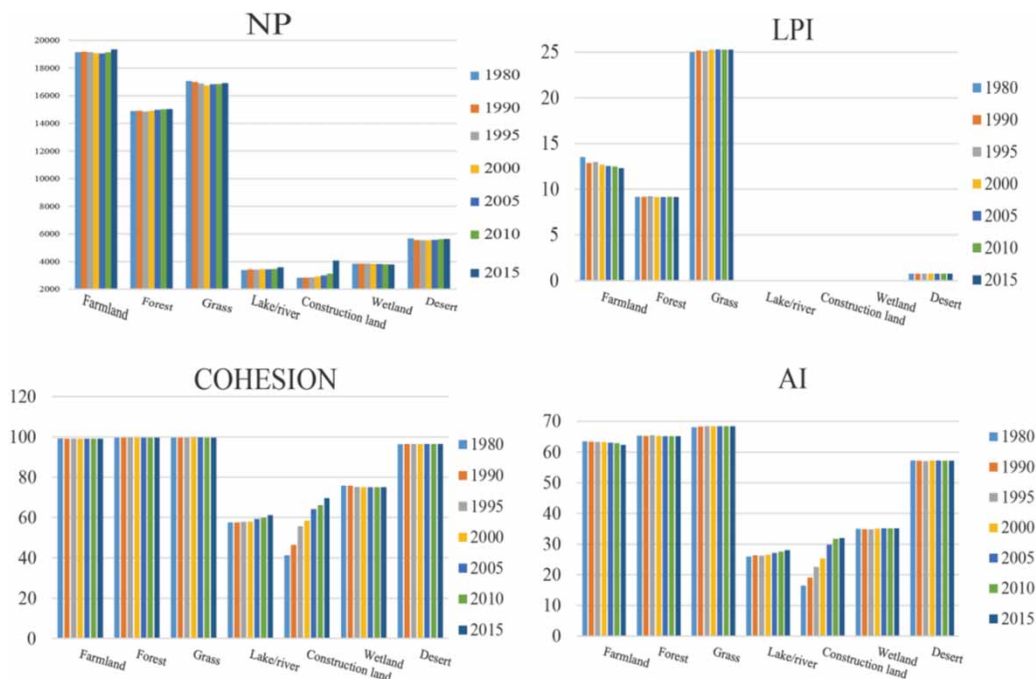
The degree of natural connectivity of patches can be expressed by the COHESION. The higher the value, the better the connectivity of landscape patches. The COHESION of farmland, forest, grassland, and desert was



**Table 2** | Area and change of various land-use types in the UYRB.

LUCC	Area (km <sup>2</sup> )						
	1980	1990	1995	2000	2005	2010	2015
Farmland	218,618	217,969	217,496	217,448	216,112	215,126	212,953
Forest	336,009	335,999	336,684	335,251	335,658	336,030	335,562
Grass	352,629	354,639	354,210	354,933	355,085	354,894	354,502
<b>Lake/River</b>	<b>5,956</b>	6,123	6,105	6,260	6,402	6,576	<b>7,070</b>
<b>Construction land</b>	<b>3,840</b>	4,155	4,547	4,986	5,713	6,325	<b>8,880</b>
Wetland	11,124	11,117	11,018	10,994	10,957	10,930	10,897
Desert	54,761	52,933	52,875	53,063	53,008	53,054	53,072

Bold values show the increase in Lake/River and Construction Land use.

**Fig. 3** | Landscape indices of the class metrics level.

higher than that of other types (Figure 3), indicating that these landscape types had relatively high connectivity, while that of lake/river, construction land, and wetland was relatively low, at less than 80%. The COHESION of construction land and lake/river increased from 41.35 in 1980 to 69.59 in 2015, while that of lake/river increased from 57.55 in 1980 to 61.20 in 2015, and the connectivity of the two was enhanced.

The AI is an index describing the degree of aggregation of landscape patches. When its value is close to 100, it means that the landscape patches are aggregated into one patch; when its value is 0, it means that the landscape patches are the most scattered (Xing *et al.*, 2021). Comparatively speaking, the AI of farmland, forest, grassland, and desert was higher, indicating that these landscape types had a higher degree of aggregation and a

concentrated spatial distribution. The AI of lake/river construction land and wetland was relatively low; these landscape types had a relatively low degree of aggregation and a dispersed spatial distribution. Further analysis of the changing process of AI patch spatial pattern (Figure 3) showed that construction land had undergone major changes. The AI of construction land almost doubled from 16.48 in 1980 to 31.96 in 2015. This was mainly because the rapid economic development since the reform and opening up had led to an increase in demand for construction land, which had made construction land more regular. The AI of lakes/ivers also experienced a certain increase, and the aggregation degree in spatial distribution was improved. The aggregation degree of patches of other land-use types in this region did not change significantly.

### 3.1.3. Characteristics of landscape structure change

At the level of landscape indicators, the SHDI increased from 1980 to 2015, while the CONTAG and the COHESION continuously decreased (Table 3). The SPLIT gradually increased from 10.30 in 1980 to 10.55 in 2015, which also indicated that the degree of landscape heterogeneity was increasing and the landscape was broken. From the changes of three key landscape indicators, LPI, LSI, and COHESION, it could be seen that the first 15 years of the study period were the most obvious period of the landscape pattern change. In 1995, the SHDI was 1.33, the landscape was dominated by a certain type. In 2015, the maximum value of SHDI was 1.35, the share of dominant landscape types had increased, and the control effect of a single component on the landscape had been weakened. The land-cover landscape types in this region were developing toward diversification and equilibrium. The decrease in the CONTAG and the COHESION also confirmed the trend of decreasing connectivity of dominant patch types and increasing degree of fragmentation of patches. The reason was that the ecological protection and management projects had been carried out, the ecological environment had been gradually restored, and the connection value of the same patches had increased in the UYRB. Grassland became the main land-use type in 2015 (Table 2). From 2000 to 2015, the larger patches were divided into many smaller patches, and the shape changes were complex and varied. The LSI presented a trend of first decreasing and then increasing. Before 2000, the study area had an extensive area of farmland and forest. After 2000, the continuous expansion of urbanization caused construction land to replace the original forest and farmland. The patterns of farmland as the main land-use type have changed. Thus, the fragmentation degree of the landscape was getting more and more serious, and the patches were distributed in a balanced trend, but the patch shapes were becoming more and more complicated.

In consideration of the continuous deterioration of the ecological environment caused by blind development, the government has implemented a series of ecological engineering constructions since the 1980s, which has

**Table 3** | Landscape pattern indices of the landscape metrics level.

Year	LPI	LSI	CONTAG	COHESION	SPLIT	SHDI
1980	24.996	178.049	40.746	99.481	10.301	1.333
1990	25.160	177.766	40.822	99.472	10.396	1.332
1995	25.111	177.300	40.819	99.473	10.390	1.333
2000	25.247	177.829	40.685	99.468	10.435	1.335
2005	25.282	178.094	40.570	99.467	10.454	1.338
2010	25.255	178.309	40.441	99.465	10.486	1.341
2015	25.241	179.545	39.920	99.461	10.545	1.352

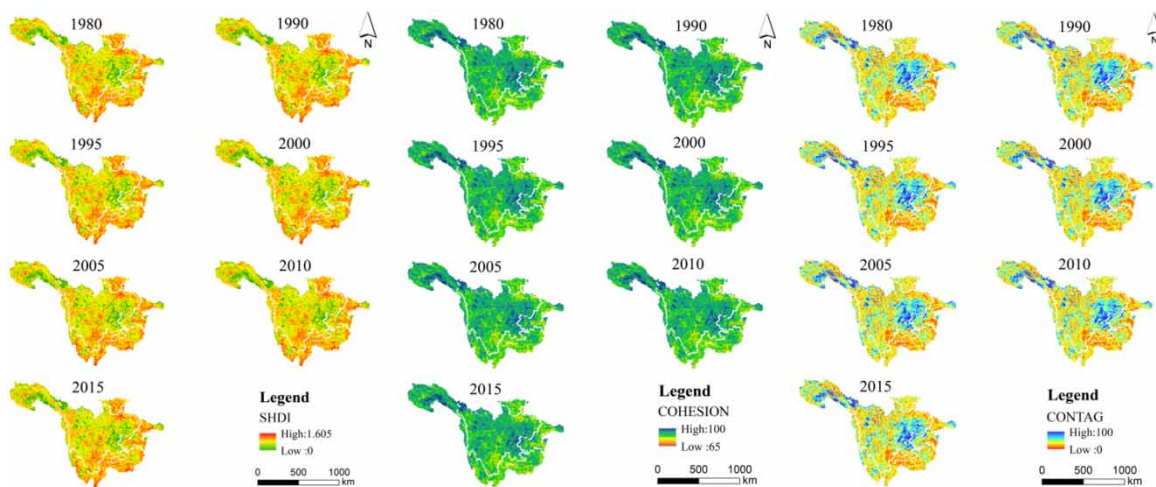
increased the diversity and heterogeneity of landscapes, helped stabilize the area of woodland and grassland, improved the quality of vegetation, and reduced some negative effects caused by the change of landscape patterns.

The southern and eastern parts of the study area were rich in landscape types, and the highest SHDI reached 1.605 (Figure 4). The central part was the Sichuan Basin, with plenty of farmland and construction land, and the western part was an alpine glacier area with low vegetation coverage. Accordingly, the SHDI in the central and western parts was relatively low. The areas with the highest values of CONTAG and COHESION were located in the Sichuan Basin and the Qinghai-Tibet Plateau, with the highest values reaching 94.461 and 99.817, respectively. This testified that the landscape was well connected, and the efficiency of information transmission between landscape patches was higher.

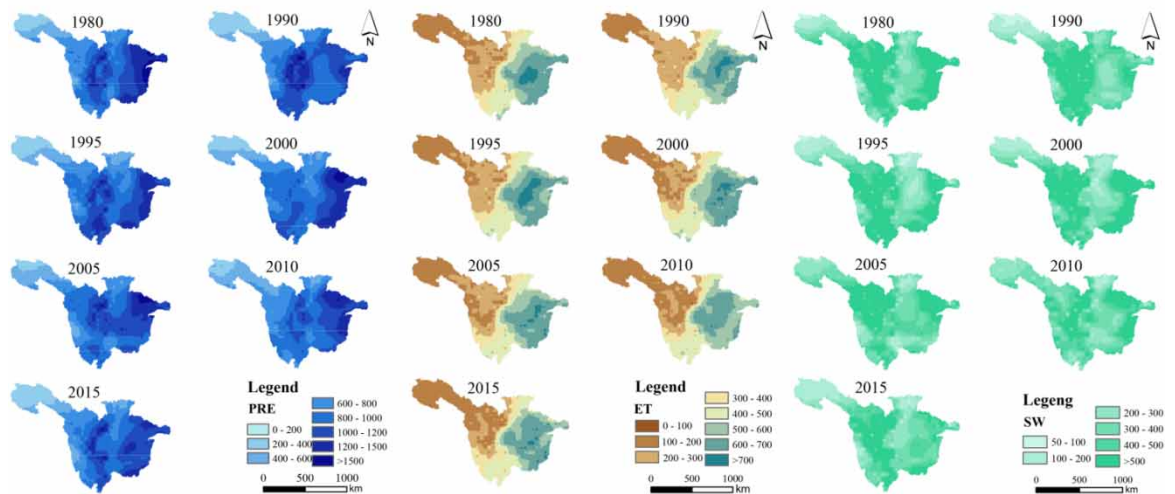
### 3.2. Spatial distribution of hydrological elements

By analyzing the spatial distribution map of precipitation (PRE) in the study area (Figure 5), it could be seen that the spatial difference of the annual mean precipitation was pretty distinct, which presented a zonal distribution on the whole, and the precipitation gradually decreased from the southeast to the northwest. Among all kinds of land-use types, the annual precipitation of farmland was the highest, and the maximum value reached 1,078 mm in 1980, followed by construction land and forest. Wetland and desert had the least annual precipitation, with an average of about 500 mm, only half that of farmland. From 1990 to 2015, the average annual precipitation in the study area decreased from 913.98 to 850.29 mm, a decrease of 6.97%. Except for forest and construction land, the annual precipitation of other land-use types showed a slow-growth trend before 2005 and then decreased gradually.

The ET change rules were quite different under various land-use types. The high-value area of ET was mainly distributed in the eastern part of the study area, the low-value area was located in the northwest area, and the difference in ET between the two places reached 700 mm. The ET of farmland and construction land ranked first, generally around 550 mm, followed by forest and lakes/river, and the ET of wetland and desert was the lowest, below 200 mm. This might be related to the urban heat island effect caused by rapid urbanization. The surface temperature of construction land is generally higher than that of other underlying surfaces, which



**Fig. 4** | SHDI, CONTAG, and COHESION of the LUCC.



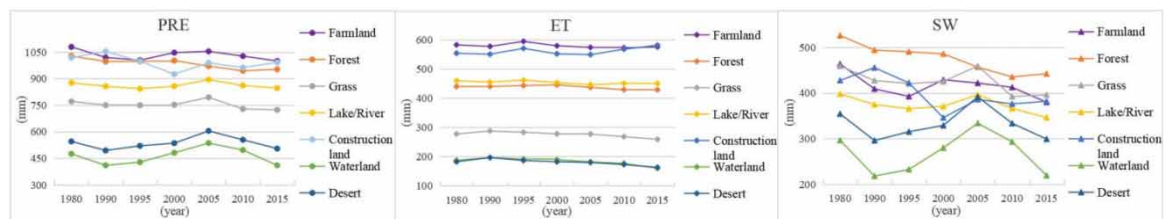
**Fig. 5** | PRE, ET, and SW in the study area.

increases the vegetation transpiration and surface evaporation in the city (Shou & Zhang, 2012). In recent decades, the ET of various land-use types had been decreasing, while this trend was not obvious.

SW decreased from 474.46 mm in 1980 to 400.46 mm in 2015, a decrease of 15.63% (Figure 6). Different types of SW also changed dramatically during the study period. The SW of forest was the highest and showed a continuous decline from 1980 to 2015, with the highest value being 525 mm in 1980 and the lowest value being 442 mm in 2015. The SW of construction land declined sharply before 2000, and then gradually increased, but the increase was not large. From the 1990s to 2005, the SW of grassland, lake/river, desert, and wetland experienced a certain increase, reached the maximum in 2005, and then decreased sharply after 2005. These results indicated that a close correlation existed between the spatial changes of the main landscape types and the hydrological element changes in the UYRB.

### 3.3. Correlation between hydrological elements and landscape pattern index

Table 4 displays the relationship between landscape pattern indices and hydrological factors at the landscape index level over the past 35 years. There was a significant negative correlation between LSI, SPLIT, SHDI, and ET, and the correlation coefficients are  $-0.907$ ,  $-0.763$ , and  $-0.911$ , respectively, which had passed the 0.05 significance test. The positive correlations between CONTAG and ET and between COHESION and SW were significant, with coefficients of 0.916 and 0.868, respectively. Conversely, SPLIT had a significant negative



**Fig. 6** | PRE, ET, and SW of the LUCC.

**Table 4** | Correlation between landscape pattern indices and hydrological factors at the landscape index level.

	LPI	LSI	CONTAG	COHESION	SPLIT	SHDI
ET	−0.518	−0.907*	0.916*	0.710	−0.763*	−0.911*
SW	−0.653	−0.526	0.689	0.868*	−0.889*	−0.729

\*Delegates a significantly correlation ( $P < 0.05$ ).

correlation with SW with a coefficient of  $-0.889$ . The correlations between other landscape indices and hydrological elements were not obvious.

CONTAG and COHESION can reflect the degree of agglomeration and connectivity within the most viewed types. A low value indicates that the landscape is composed of many discrete small patches; on the contrary, a high value indicates that the landscape is composed of large patches with higher connectivity (Guo *et al.*, 2020). Table 4 shows that the reduction of SW and ET has a great impact on the connectivity and spread of the landscape. As patches continue to merge, the adjacent distance between patches increases, and the spatial distribution becomes more scattered and fragmented (Zhang, 2018). The decreasing trend of ET is related to the monitoring ability of vegetation evaporation. The total NPs in the landscape patterns of the watershed increased, the shape of patches became complex, and the landscape presented stronger heterogeneity on the whole (Zhao *et al.*, 2019a). SPLIT reflected the degree of separation of different patches, and the decrease of SW leads to an increase in the degree of separation of patch landscape. SHDI and ET were significantly negatively correlated, indicating that ET had a great impact on landscape diversity and richness.

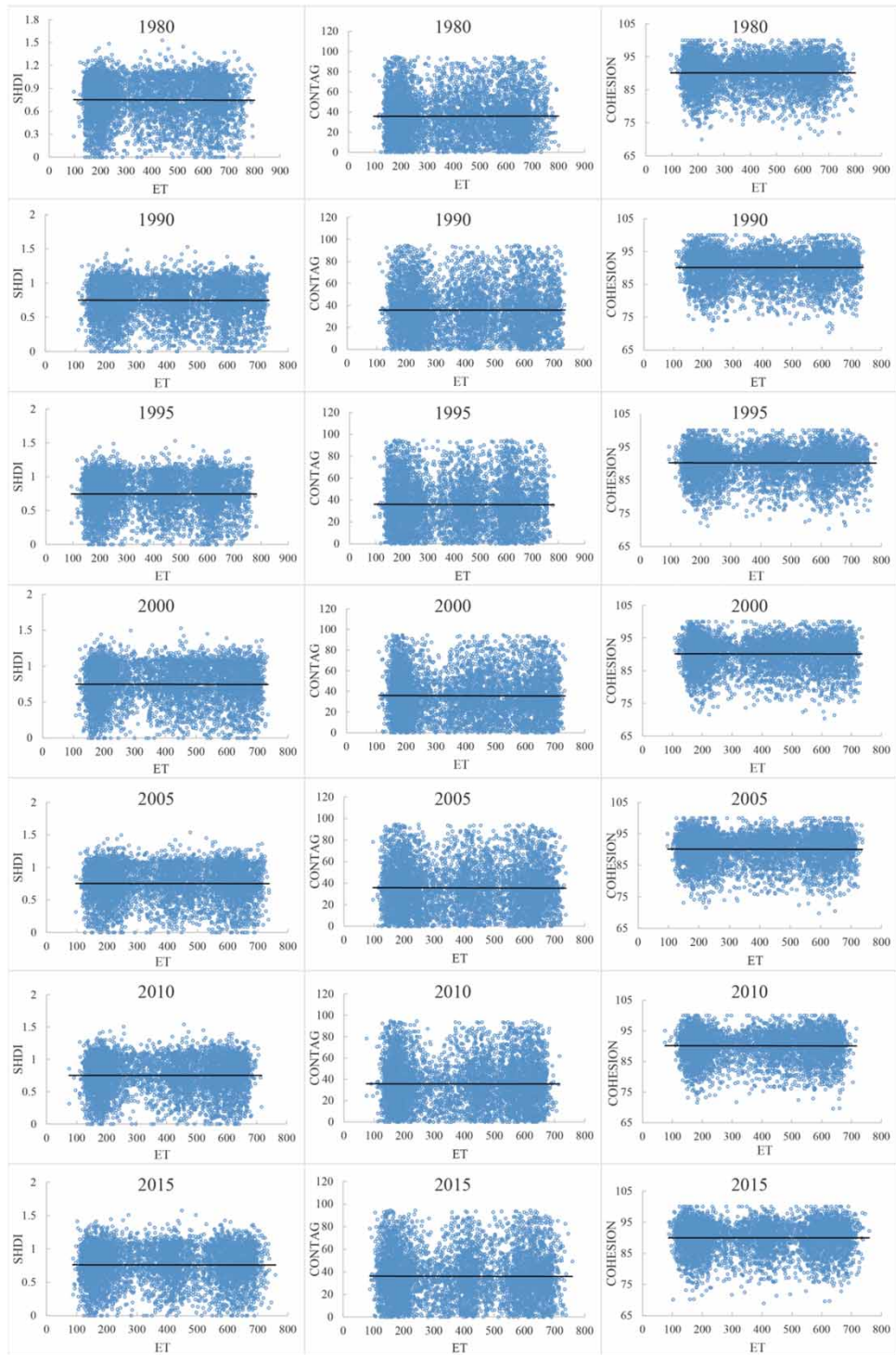
The correlation between hydrological elements and landscape indices shows that the direction of landscape type conversion is related to the change of ET and soil water storage variables on the time scale. The process of water balance could affect the diversity and aggregation degree of various landscape types.

In order to further determine the relationship between landscape patterns and hydrological factors, the response characteristics of landscape patterns to hydrological factors were analyzed based on the landscape pattern index and spatial distribution maps of SW and ET. Before using spatial analysis tools to extract data, 6,000 points were randomly selected with ArcGIS software to create scatter plots and conduct statistical analysis (Figures 7 and 8). The landscape index aggregates most in the range of ET of 150–700 mm and SW of 50–1,000 mm. This is because human activities are more frequent in this region. Due to the intensity of human activities, SHDI and CONTAG are higher, and COHESION is lower.

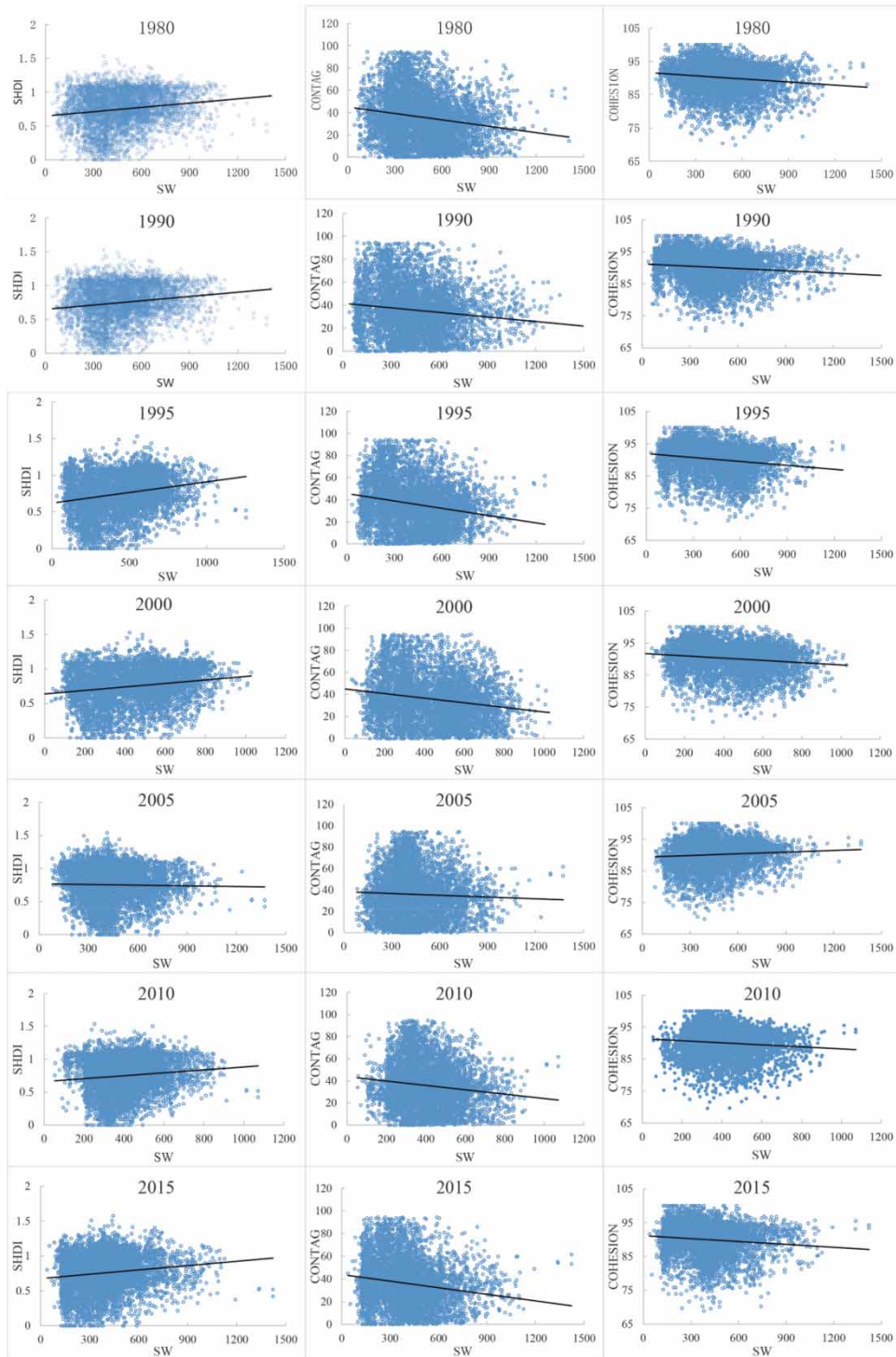
With the increase of SW, SHDI showed an upward trend, and CONTAG and COHESION displayed a downward trend. However, the changing trend of SHDI, CONTAG, and COHESION with ET was not obvious.

By analyzing the relationship between the landscape index and SW and ET (Table 5), it could be seen that a certain correlation existed between SW, ET, and the above three landscape indices. The correlation between SHDI and SW was positive, but the correlation was more obvious in the 1990s and not obvious after that. Apart from 2005 and 2010, CONTAG, COHESION, and SW in other years were significantly negatively correlated, which demonstrated that landscape connectivity and landscape contagion decreased significantly with the increase of SW in spatial scale. This might be related to the two severe drought events in the southwest in 2006 and 2009 (Xu *et al.*, 2013; Li *et al.*, 2014). SHDI, CONTAG, and COHESION were positively correlated with ET, while the correlation was not significant. Also, landscape diversity had a significant negative correlation with landscape connectivity and landscape contagion, and landscape contagion had a significant positive correlation with landscape connectivity. A higher degree of landscape contagion indicated the presence of some major patches in the landscape, leading to higher connectivity between patches.





**Fig. 7** | Correlation between landscape pattern indices and ET.



**Fig. 8** | Correlation between landscape pattern indices and SW.

**Table 5** | Relationships between EWRs and landscape pattern indices.

Year	Index	SW	SHDI	CONTAG	COHESION	Index	ET	SHDI	CONTAG	COHESION
1980	SW	1	0.254	−0.264	−0.362*	ET	1	0.027	0.044	0.016
	SHDI		1	−0.634*	−0.868*	SHDI		1	−0.634*	−0.868*
	CONTAG			1	0.538*	CONTAG			1	0.538*
	COHESION				1	COHESION				1
1990	SW	1	0.335*	−0.333*	−0.333*	ET	1	0.02	0.021	0.038
	SHDI		1	−0.607*	−0.864*	SHDI		1	−0.607*	−0.864*
	CONTAG			1	0.504*	CONTAG			1	0.504*
	COHESION				1	COHESION				1
1995	SW	1	0.311*	−0.376*	−0.345*	ET	1	0.017	0.022	0.037
	SHDI		1	−0.600*	−0.861*	SHDI		1	−0.600*	−0.861*
	CONTAG			1	0.498*	CONTAG			1	0.498*
	COHESION				1	COHESION				1
2000	SW	1	0.309*	−0.302*	−0.380*	ET	1	0.023	0.007	0.001
	SHDI		1	−0.599*	−0.847*	SHDI		1	−0.599*	−0.847*
	CONTAG			1	0.502*	CONTAG			1	0.502*
	COHESION				1	COHESION				1
2005	SW	1	−0.039	−0.13	0.01	ET	1	0.023	0.007	0.001
	SHDI		1	−0.589*	−0.843*	SHDI		1	−0.599*	−0.847*
	CONTAG			1	0.505*	CONTAG			1	0.502*
	COHESION				1	COHESION				1
2010	SW	1	0.14	−0.252	−0.237	ET	1	0.011	0.026	0.016
	SHDI		1	−0.588*	−0.843*	SHDI		1	−0.588*	−0.843*
	CONTAG			1	0.507*	CONTAG			1	0.507*
	COHESION				1	COHESION				1
2015	SW	1	0.248	−0.386*	−0.268*	ET	1	0.024	0.058	0.026
	SHDI		1	−0.590*	−0.847*	SHDI		1	−0.590*	−0.847*
	CONTAG			1	0.494*	CONTAG			1	0.494*
	COHESION				1	COHESION				1

\*Delegates significantly correlation ( $P < 0.05$ ).

#### 4. DISCUSSION AND CONCLUSIONS

Based on hydrometeorological element data and land-use data, this study looked at the spatial distribution of hydro-meteorological elements in the UYRB, the spatiotemporal characteristics of land-use and landscape patterns, and analyzed the correlation between water balance processes and landscape indices from 1980 to 2015. The study of large-scale and long-term watershed landscape patterns can grasp the overall condition of the watershed and provide a certain basis and reference for subsequent research. The main conclusions and discussions are as follows:

- (1) *Changes of hydrometeorological elements*: Climate change plays a key role in the evolution of landscape patterns in the UYRB. The spatial distribution of precipitation varies greatly. Among the various types of land

use, the annual precipitation of farmland is the largest (1,050 mm), followed by forest and construction land. The changes of ET are not great in the whole study area, but are obvious under different land-use types. The highest ET was in farmland and building land, which was about 550 mm, and the lowest ET was in wetland and desert, which was below 200 mm. The soil water storage variable had undergone drastic changes, and the SW of the forest was the highest, showing a downward trend year by year. The SW of grassland, lakes/river, desert, and wetland exhibited a fluctuating state of 'decrease-increase-decrease'. These findings were consistent with previous studies on the variation of hydrological elements in the UYRB (Wang *et al.*, 2010; Wang *et al.*, 2015). During 1980–2015, both PRE and SW decreased to a certain extent, and both showed a trend of 'sudden increase' in 2005. It can be seen that 2005 is a year with great changes in hydrological elements in the study area.

- (2) *Change of landscape pattern*: The process of water balance has both positive and negative effects on landscape pattern changes. The regions with great hydrological regime changes produced high diversity of landscape types, but low diversity of ecosystem and community types within the landscape. On the contrary, the regions with little hydrological regime change and no obvious humidity gradient produced low diversity of landscape types, but high diversity of landscape internal structure (Liu *et al.*, 2004). Landscape index analysis showed that the degree of landscape fragmentation of rivers/lakes and construction land in the study area gradually decreased, the connectivity increased, and the change of construction land was more obvious than that of rivers/lakes. From the perspective of spatial distribution, the NPs in farmland, forest, and grassland was the largest during the study period, and they occupied a dominant position in the study area. With the decrease of farmland wetland and desert area, construction land and lake/river have different degrees of expansion. At the landscape structure level, SHDI and SPLIT had increased, indicating that the control degree of dominant landscape components was weakened. The decrease of CONTAG and COHESION showed that the degree of patch fragmentation had increased, and the degree of landscape heterogeneity had gradually increased. The LSI decreased first and then increased, which meant that the fragmentation of the landscape was getting more and more serious, and the shape of the patches was getting more and more complicated.
- (3) *Correlation between landscape indices and hydrological factors*: Previous studies have shown that precipitation has a significant effect on vegetation growth and development in arid and semi-arid regions, but the effect is weak in the humid climate of the UYRB (Guan *et al.*, 2018). Therefore, this study focuses on the impact of SW and ET on landscape. The distribution of soil water has a great influence on the distribution of landscape types. And it is affected by the topographic characteristics and the determined hydrological conditions, which creates the difference of landscape types and their zonality. Therefore, the distribution of soil water has a macroscopic zonality and a microscopic locality (Ma & Zhao, 2007). Liu & Li (2006) pointed out that the landscape pattern change is related to soil water, soil moisture is the decisive zonal soil water-holding capacity with appropriate conditions, and other variables related to soil water play an important role in landscape structure and dynamic change. At the level of landscape index, the correlation between landscape indices and hydrological elements was clear, but the degree of correlation was different. On the time scale, the correlation between hydrological factors and landscape indices was obvious. LSI, SPLIT, and SHDI were significantly negatively correlated with ET, while CONTAG was significantly positively correlated with ET. SPLIT had a significant negative correlation with SW, and COHESION had a significant positive correlation with SW. The results showed that with the decrease of ET and soil water storage variables, patches became more scattered and landscape patterns became more broken. Moreover, from the perspective of spatial distribution, SHDI was positively correlated with SW in the 1990s, indicating that the increase in SW improved landscape diversity. CONTAG and COHESION were significantly negatively correlated

with SW (except for 2005 and 2010), and the connectivity and cohesion of the landscape decreased with the increase of SW. SHDI, CONTAG, and COHESION were positively correlated with ET, but the correlation was not significant. The correlation coefficients between SW and the three groups of landscape pattern indexes were higher than those between ET and the three, which meant that soil water was more correlated with landscape pattern characteristics. The change of soil water was the main cause of landscape heterogeneity.

The idea of the water balance method is to take the ecosystem of the whole study area as a whole and consider the water balance from the inflow and outflow of the whole water flow (Zhao *et al.*, 2019a, 2019b). This method analyzes the problem from a macro perspective and takes the ecosystem as the entire research object. The calculation process is relatively simple, easy to operate, and easy to understand (Yu & Chen, 1996). The whole analysis involves the following three types of data: precipitation, ET, and soil water storage variable. The calculation of ET overcomes the shortcoming that the evaporation of land surface is greater than that of precipitation. However, this method does not consider the influence of factors such as the interception of the canopy litter layer on the groundwater surface, so the calculation result is not accurate. In the calculation of soil water content, although the effects of precipitation, evaporation, and topography are considered, the effects of melting snow, lakes, rivers, and agricultural irrigation are not considered. To improve the accuracy of the calculations, the Standardized Soil Moisture Index (SSMI) could be introduced to assess the soil water deficit, which had some inconsistencies with the data used in this study. And the model had been proven to be suitable for assessing soil water content in the UYRB (Wang *et al.*, 2015).

The decrease of soil water storage variables in the basin will put pressure on the special and complex ecosystem in the UYRB (Ma & Zhao, 2007). Since ecological processes have obvious spatiotemporal scale characteristics, the study of the relationship between water balance and ecological processes also provides a scientific basis for the establishment of the corresponding ecological processes model and scale transformation. At the same time, the change of landscape patterns in the UYRB may also be influenced by other natural factors (slope, elevation, etc.) and human activities. The accuracy and comprehensiveness of the index system of driving factors of landscape pattern changes need to be improved. How to integrate hydrometeorological conditions and other dynamic driving factors in the study area to expand the research results in other areas with similar/different land-use/-cover situations is the focus of further research. With an in-depth understanding of the relationship between economic development and sustainable utilization of resources, we must pay more attention to different natural ecosystem landscapes, explore the driving forces of natural landscapes, and put forward effective conservation strategies.

## ACKNOWLEDGMENTS

The work was supported by the National Key Research and Development Program (Grant No. 2016YFA0601503) and the National Natural Science Foundation of China (Grant Nos U2040212 and 52079008).

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.



## REFERENCES

- Blackburn, A., Anderson, C. J., Veals, A. M., Tewes, M. E., Wester, D. B., Young, J. H., DeYoung, R. W. & Perotto-Baldivieso, H. L. (2020). [Landscape patterns of ocelot-vehicle collision sites](#). *Landscape Ecology*. <https://doi.org/10.1007/s10980-020-01153-y>.
- Chen, J. & Li, T. (2019). Analysis on the spatial variation of ecosystem service value in China. *Journal of Peking University (Natural Sciences)* 55(5), 951–960. doi:10.13209/j.0479-8023.2019.063.
- Chen, L., Sun, R. & Liu, H. (2013a). [Research progress on ecological and environmental effects of urban landscape pattern evolution](#). *Acta Ecologica Sinica* 33(4), 1042–1050.
- Chen, X., Song, L., Guo, Z., Gao, X. & Zhang, Q. (2013b). Climate change characteristics and impacts in the Three Gorges Reservoir area and the upper reaches of the Yangtze River. *Resources and Environment in the Yangtze Basin* 22(11), 1466–1471.
- Chen, J., Gao, C., Zeng, X., Xiong, M., Wang, Y., Jing, C., Krysanova, V., Huang, J., Zhao, N. & Su, B. (2017). [Assessing changes of river discharge under global warming of 1.5 °C and 2 °C in the upper reaches of the Yangtze River Basin: approach by using multiple – GCMs and hydrological models](#). *Quaternary International* 45(3), 63–73. <http://dx.doi.org/10.1016/j.quaint.2017.01.017>.
- Feng, J., Li, Q., Liang, C., Feng, J., Zhang, X., Le, Y. & Gao, J. (2020). Dynamic analysis of hydrological connectivity of wetlands in the Yellow River estuary based on landscape index. *Journal of Beijing Normal University (Natural Science)* 57(01), 12–21.
- Gao, Q. (2020). *The Process and Prediction of Ecohydrological Change in the Dawen River Basin*. Jinan University. <http://dx.doi.org/10.27166/d.cnki.gsdcc.2020.000199>.
- Guan, Q., Yang, L., Pan, N., Lin, J., Xu, C., Wang, F. & Liu, Z. (2018). [Greening and browning of the Hexi Corridor in Northwest China: spatial patterns and responses to climatic variability and anthropogenic drivers](#). *Remote Sensing* 10(8), 1270. <http://dx.doi.org/10.3390/rs10081270>.
- Guo, S., Bai, H., Meng, Q., Zhao, T., Huang, X. & Qi, G. (2020). Changes and driving factors of landscape pattern of woodland and grassland in Qinling Mountains. *Acta Ecologica Sinica* 40(1), 130–140.
- Jiang, Y., Li, S., Hong, D. & Chen, W. (2012). [Characteristics of climate change and its impact on regional environment in the source region of rivers on the Qinghai-Tibet Plateau in recent 40 years](#). *Journal of Mountain Science* 30(4), 461–469. <http://dx.doi.org/10.16089/j.cnki.1008-2786.2012.04.017>.
- Jiang, L., Guli, J., Bao, A., Guo, H. & Felix, N. (2017). [Vegetation dynamics and responses to climate change and human activities in Central Asia](#). *Science of the Total Environment* 599–600, 967–980. <http://dx.doi.org/10.1016/j.scitotenv.2017.05.012>.
- Koichiro, T. (1979). Empirical equations for evaporation as calculated from monthly mean temperature and rainfall. *Weather* 26(12), 29–32.
- Lei, Y., Long, A., Deng, M., Li, X. & Zhang, Y. (2012). Climate change and its impact on water resources in the middle reaches of the Irtys River Basin during 1926–2009. *Journal of Glaciology and Geocryology* 34(04), 912–919.
- Li, S., Wang, G. & Deng, W. (2008). [Advances in wetland landscape pattern and hydrological processes](#). *Journal of Chemical Ecology* 27(6), 1012–1020. <http://dx.doi.org/10.13292/j.1000-4890.2008.0198>.
- Li, J., Zhang, Q., Chen, X. & Jiang, T. (2011). Study on the ecological water demand in the main stream of the Yellow River considering hydrological variation. *Journal of Geographical Sciences* 66(01), 99–110.
- Li, Q., Li, P., He, Y. & Chen, D. (2018). [Correlation analysis of main hydrometeorological elements in the middle and lower reaches of Lancang River Basin](#). *Journal of Irrigation and Drainage* 37(9), 100–107. <http://dx.doi.org/10.13522/j.cnki.ggps.2017.0614>.
- Li, S., Wang, G. & Deng, W. (2019). [Influence of hydrology process on wetland landscape pattern: a case study in the Yellow River Delta](#). *Ecological Engineering* 35(12), 1719–1726. <http://dx.doi.org/10.1016/j.ecoleng.2009.07.009>.
- Li, S., Shen, Z., Ke, Y., Li, J., Xu, Z., Wang, H., Jiao, S., Li, L. & Li, L. (2021). [Spatiotemporal changes of land use landscape in Daqinghe River Basin from 1974 to 2019](#). *Research of Soil and Water Conversation* 28(01), 195–203 + 210. <http://dx.doi.org/10.13869/j.cnki.rswc.2021.01.025>.
- Li, Y., Ren, F., Li, Y., Wang, P. & Yan, H. (2014). [Characteristics of regional meteorological drought events in Southwest China during 1960–2010](#). *Journal of Meteorological* 72(02), 266–276. <https://doi.org/10.11676/qxxb2014.026>.
- Liu, Y. (2017). Effectiveness of landscape index coupling landscape pattern with soil erosion. *Acta Ecologica Sinica* 37(15), 4923–4935.

- Liu, H. & Li, Z. (2006). Spatial gradient pattern of wetland landscape in watershed and its influencing factors. *Acta Ecologica Sinica* 26(01), 213–220.
- Liu, H., Zhang, S. & Lv, X. (2004). Temporal and spatial changes of wetland landscape structure in Sanjiang Plain. *Journal of Geographical Sciences* (03), 391–400.
- Liu, J., Zhao, D. & Tian, X. (2014). Dynamic changes and driving forces of land use landscape pattern in Sanjiang Plain in 1954, 2010. *Acta Ecologica Sinica* 34(12), 3234–3244.
- Liu, Y., Zhang, X. & Wu, Q. (2018). Effects of landscape pattern change on non-point source pollution in coastal zone. *Journal of Coastal Research* 85(1), 756–760. <http://dx.doi.org/10.2112/SI85-152.1>.
- Lou, J. (2015). *Vegetation Dynamic Change and Water Resources Effect in Chaohe River Basin*. Beijing Forestry University, Beijing.
- Ma, J. & Zhao, C. (2007). Landscape pattern change and its driving factors in Xinglong Mountain region. *Acta Ecologica Sinica* 27, 3206–3214.
- Ma, G., Wang, Y., Xiang, B., Wang, J. & Hu, Y. (2012). Impact of land use on non-point source pollution in the upper reaches of the Yangtze River Basin and its differences. *Journal of Agro-Environment Science* 31(04), 791–797.
- Ma, Z., Wang, H., Yang, F. & Fu, X. (2020). Restoration and sustainable development of forest ecosystem in subtropics hilly red soil region based on long-term observation. *Proceedings of the Chinese Academy of Sciences* 35(12), 1525–1536. <http://dx.doi.org/10.16418/j.issn.1000-3045.20201209001>.
- Pan, K., Wu, N., Pan, K. & Chen, Q. (2004). Discussion on some problems of constructing ecological barrier in the upper reaches of the Yangtze River. *Acta Ecologica Sinica* 03, 617–629.
- Pan, Y., Ying, Z., Li, H., Liu, C., Zhang, H. & Guan, B. (2019). Changes of wetland landscape pattern in Poyang Lake under hydrological processes and sand mining activities. *Wetland Science* 17(03), 286–294. <http://dx.doi.org/10.13248/j.cnki.wetlandsci.2019.03.004>.
- Ramallo, C. E., Laliberté, E., Poot, P. & Hobbs, R. J. (2014). Complex effects of fragmentation on remnant woodland plant communities of a rapidly urbanizing biodiversity hotspot. *Ecology* 95, 2466–2478. <https://doi.org/10.1890/13-1239.1>.
- Ren, P., Cheng, W., Hong, B. & Zhou, J. (2013). Threat assessment and spatial distribution of ecosystem degradation in the upper reaches of the Yangtze River under the framework of PSDR theory. *Geographical Science* 33(02), 189–194. <http://dx.doi.org/10.13249/j.cnki.sgs.2013.02.009>.
- Rong, L. (2007). *Analysis on Landscape Pattern of Xixi Wetland in Hangzhou*. Zhejiang University, Zhejiang.
- Shou, Y. & Zhang, D. (2012). Research progress and prospect of urban heat island effect. *Acta Meteorologica Sinica* 70(3), 338–353.
- Wang, X. (2017). *Study on the Relationship Between Sand-Fixing Vegetation Pattern and Hydrological Process in Gurbantunggut Desert*. Xinjiang Agricultural University. <http://dx.doi.org/10.27431/d.cnki.gxnyu.2017.000012>.
- Wang, G., Liu, G. & Chang, J. (2005). A review of watershed scale ecohydrological research. *Acta Ecologica Sinica* 25(4), 892–903.
- Wang, Y., Jiang, T. & Liu, B. (2010). Trends of actual evaporation in the Yangtze River Basin. *Journal of Geographical Sciences* 65(9), 1079–1088.
- Wang, W., Wang, P. & Cui, W. (2015). Comparative analysis of land water storage and multi-source hydrological data in the Yangtze River Basin. *Advances in Water Science* 26(06), 759–768. <http://dx.doi.org/10.14042/j.cnki.32.1309.2015.06.001>.
- Wang, M., Wan, X., Zhong, P., Zhang, Y. & Liu, C. (2016). Characteristics and spatial-temporal evolution of precipitation in the upper reaches of the Yangtze River. *South-North Water Diversion and Water Resources Science and Technology* 14(04), 65–71. <http://dx.doi.org/10.13476/j.cnki.nsbdk.2016.04.011>.
- Wu, X., Shen, Z. & Liu, R. (2008). Land use/cover change and regional differentiation in the upper reaches of the Yangtze River. *Journal of Applied Basic and Engineering Sciences* 16, 819–829. <http://dx.doi.org/10.16058/j.issn.1005-0930.2008.06.017>.
- Wu, N., Gao, J., Sudbilig, Luo, Z. & Li, D. (2010). Land use/cover change under different topographic conditions in the upper reaches of the Yangtze River. *Resources and Environment in the Yangtze River Basin* 19(03), 268–275.
- Wu, J., Fang, S., Liu, B., Sheng, Z. & Du, J. (2020). Wetland landscape pattern evolution and its driving mechanism in Shuangyang River Basin of Wuyue River. *Acta Ecologica Sinica* 40(13), 4279–4290.
- Xiao, J., Ouyang, H., Fu, B. & Niu, H. (2003). Forest ecosystem health assessment indicators and their application in China. *Journal of Geographical Sciences* 58(06), 803–809.
- Xie, G., Zhen, L., Lu, C., Xiao, Y. & Chen, C. (2008). An expert knowledge-based approach to value ecosystem services. *Journal of Natural Resources* 23(5), 911–919.

- Xing, L., Wang, Z. & Tu, Y. (2021). Spatial-temporal evolution of natural mountain landscape pattern in karst cities in central Guizhou: a case study of Anshun City. *Acta Ecologica Sinica* 41, 1291–1302.
- Xiong, Y., Zhou, J., Chen, L., Jia, B., Sun, N., Tian, M. & Hu, G. (2020). Land use pattern and vegetation cover dynamics in the Three Gorges Reservoir (TGR) intervening basin. *Water* 12(7). <http://dx.doi.org/10.3390/w12072036>.
- Xu, M., Ye, B. & Zhao, Q. (2013). Spatiotemporal variation of GRACE water storage in the Yangtze River Basin from 2002 to 2010. *Progress in Geography* 32(01), 68–77. <http://dx.doi.org/10.3724/SP.J.1033.2013.00068>.
- Xu, S., Li, S.-L., Zhong, J. & Li, C. (2020). Spatial scale effects of the variable relationships between landscape pattern and water quality: example from an agricultural karst river basin, Southwestern China. *Agriculture, Ecosystems & Environment*. <http://dx.doi.org/10.1016/j.AGEE.2020.106999>.
- Yan, D., He, Y. & Deng, W. (2001). Watershed ecohydrological pattern and water environment safety regulation. *Resources and Environment*, 55–57.
- Yan, D., He, Y., Wang, H., Qing, D. & Wang, J. (2005). A review of studies on the impact of ecohydrological processes on water environment. *Advances in Water Science* 16(5), 747–752. <https://doi.org/10.14042/j.cnki .32.1309.2005.05.024>.
- Yang, Z., Cu, B. & Huang, G. (2006). Water environmental effect and ecological safety regulation of wetland water ecological process in Huang-Huai-Hai area. *Advances in Earth Science* 21(11), 1119–1126.
- Ye, Y., Liang, L., Gong, J., Jiang, Y. & Wang, H. (2014). Temporal and spatial evolution of precipitation structure in the upper reaches of the Yangtze River Basin. *Advances in Water Science* 25(02), 164–171. <http://dx.doi.org/10.14042/j.cnki.32.1309.2014.02.002>.
- Yu, X. & Chen, L. (1996). Water balance of shelterbelt ecosystem in loess region. *Acta Ecologica Sinica* 16(3).
- Yu, S., Xin, Y. & Liu, J. (2011). Review of status of urban landscape pattern. *Agricultural Science and Technology and Information (Modern Garden)* 19(5), 467–478.
- Zhang, R. (2018). Hydrological regime and wetland landscape pattern change in the upper reaches of Heihe River. BJFU. <http://dx.doi.org/10.26949/d.cnki.gblyu.2018.000025>.
- Zhang, J. (2019). *Study on Evapotranspiration in the Songhua River Basin under the Background of Climate Change Based on Budyko Hypothesis*. North West Agriculture and Forestry University, Zhejiang.
- Zhang, Y., Wang, L., Zou, C., Hu, X. & Xue, L. (2010). Study on balance characteristics of water supply and demand and ecological adaptability of upland farming system in high-temperature and drought-prone areas. *Research of Soil and Water Conservation* 17(6), 95–100.
- Zhao, F., Li, H., Li, C., Cai, Y., Wang, X. & Liu, Q. (2019a). Analyzing the influence of landscape pattern change on ecological water requirements in an arid/semiarid region of China. *Journal of Hydrology* 578(C). <https://doi.org/10.1016/j.jhydrol.2019.124098>.
- Zhao, J., Jia, J., Jia, G. & Chen, L. (2019b). Water balance and its influencing factors of typical plantation ecosystem in northern China under drought conditions. *Journal of Chemical Ecology* 38(11), 3254–3263. <https://doi.org/10.13292/j.1000-4890.201911.016>.
- Zhou, X., Wang, L. & Deng, B. (2011). Ecosystem health assessment in the Yangtze River estuary and adjacent sea areas. *Journal of Hydraulic Engineering* 42(10), 1201–1208. <http://dx.doi.org/10.13243/j.cnki.slxh.2011.10.006>.